

MICROSTRUCTURE AND MECHANICAL PROPERTIES OF EXTRUDED GAMMA MET PX

S. L. Draper,¹ G. Das,² I. Locci,¹ J.D. Whittenberger,¹ B.A. Lerch,¹ and H. Kestler³

¹NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135–3191 USA

²Pratt & Whitney, 400 Main Street, East Hartford, Connecticut 06108 USA

³PLANSEE AG, A–6600, Reutte Austria

Abstract

A gamma TiAl alloy with a high Nb content is being assessed as a compressor blade material. The microstructure and mechanical properties of extruded Ti-45Al-X(Nb,B,C) (at.%) were evaluated in both an as-extruded condition and after a lamellar heat treatment. Tensile behavior of both as-extruded and lamellar heat treated specimens was studied in the temperature range of RT to 926 °C. In general, the yield stress and ultimate tensile strength reached relatively high values at room temperature and decreased with increasing deformation temperature. The fatigue strength of both microstructures was characterized at 650 °C and compared to a baseline TiAl alloy and to a Ni-base superalloy. Tensile and fatigue specimens were also exposed to 800 °C for 200 h in air to evaluate the alloy's environmental resistance. A decrease in ductility was observed at room temperature due to the 800 °C exposure but the 650 °C fatigue properties were unaffected. Compressive and tensile creep testing between 727 and 1027 °C revealed that the creep deformation was reproducible and predictable. Creep strengths reached superalloy-like levels at fast strain rates and lower temperatures but deformation at slower strain rates and/or higher temperature indicated significant weakening for the as-extruded condition. At high temperatures and low stresses, the lamellar microstructure had improved creep properties when compared to the as-extruded material. Microstructural evolution during heat treatment, identification of various phases, and the effect of microstructure on the tensile, fatigue, and creep behaviors is discussed.

Introduction

The turbine based combined cycle program (TBCC) for the next generation launch vehicle has targeted gamma titanium aluminide as a potential compressor and structural material. The high compressor inlet and exit temperatures in the TBCC engine require higher temperature materials than conventional Ti alloys and the stringent thrust to weight requirements of the TBCC engine requires low density material to be utilized wherever possible. Gamma alloys offer higher temperature capability along with low density and high stiffness. A high temperature, high strength γ -TiAl alloy with a high Nb-content (Gamma MET PX¹) was selected for evaluation. In this paper, the results of an initial study on the microstructure of Gamma Met PX in both the as-extruded and lamellar heat-treated conditions and the influence of the microstructure on the tensile, creep, and fatigue properties are reported.

Materials and Procedures

Triple vacuum arc remelted Ti-45Al-X(Nb,B,C) (at.%) gamma TiAl ingots were extruded in two steps at a nominal billet preheat temperature of 1280 °C to a final extrusion ratio of 100:1. Cylindrical bars of 12.7 mm diameter by 152 mm long were produced and tensile, creep, and fatigue specimens were machined from the as-extruded bars. A fully lamellar microstructure was formed by heat treating at 1340 °C for 40 min in vacuum followed by furnace cooling. Two specimen production sequences were utilized for the lamellar microstructure: 1) as-extruded bars were heat treated at 1340 °C and then machined into tensile and creep samples and 2) as-extruded bars were machined into tensile and fatigue samples and then heat treated to form the lamellar microstructure. The tensile, tensile creep and fatigue specimens were machined using low-stress grinding with the testing directions parallel to the extrusion direction. Compressive creep specimens were electrodischarged machined (EDM) and tested with the as EDM'ed surface. Selected as-extruded and lamellar tensile specimens and as-extruded fatigue specimens were also exposed to 800 °C for 200 h in air to determine the alloy's environmental resistance.

The tensile specimens were tested in air at temperatures ranging from room temperature to 926 °C using a constant strain rate of $1 \times 10^{-4} \text{ s}^{-1}$. Strain was measured with a contacting 12.7-mm-gage-length axial extensometer. High cycle fatigue specimens were tested at 650 °C with a frequency of 100 Hz and a load ratio, R , of 0.05 ($R = \sigma_{\min}/\sigma_{\max}$). Due to the flat nature of γ -TiAl's S-N (stress versus cycles to failure) curve, step fatigue tests were used to determine the maximum fatigue strength [1–3]. If the sample survived 10^6 cycles, the stress was increased by 13.8 MPa and run to failure or an additional 10^6 cycles. The stress level was increased until failure occurred. Fatigue strength was taken as the stress at the next-to-last step, i.e., the stress representing the fatigue threshold. The use of step fatigue testing avoided using a large number of samples due to runouts, as each sample was forced to fail. It should be noted that a potential drawback to such testing is the possibility of coxing, which would lead to fatigue strengths that were meaningless for design. Coxing was investigated as part of another study [3] and shown not to occur in Ti-48Al-2Cr-2Nb (at.%).

The compressive creep behavior was determined in air by compressing samples under constant velocity conditions in a universal testing machine and under constant load creep conditions in lever arm creep frames. For both test methods, the recorded data were converted to true steady state compressive stresses, strains, and strain rates from the final specimen length and the assumptions that volume was conserved and all plastic

¹Gamma MET PX is a trademark of PLANSEE AG, Austria. Alloy composition is based on TNB alloys developed by GKSS Research Center, Germany.

deformation occurred in the specimen. Tensile creep testing was conducted in lever arm test frames under single engineering stress to failure in air where strain was monitored by an extensometer attached to the grooves cut into the shoulders of the test specimen. All deformation observed by the extensometer was assumed to have occurred within the gage section, and such elongation-time results were converted to true stress and true strains by assuming the conservation of volume.

Results and Discussion

Microstructure

The as-extruded bars had a duplex microstructure with a high volume fraction of lamellar grains (nearly lamellar microstructure) with a grain size of approximately 20 μm . A small volume fraction of fine, $\sim 4 \mu\text{m}$ in diameter, gamma grains were located in between lamellar colonies and at the periphery of the extruded bars, figure 1. The development of a duplex microstructure suggests that the resulting extrusion temperature was below the alpha transus temperature of the alloy, which was determined from differential scanning calorimetry to be $\sim 1310^\circ\text{C}$. In longitudinal sections, flow lines resulting from the extrusion were readily observed and were nearly symmetrical about the extrusion axis. The lamellar grains were highly strained as revealed by the distortion of both the α_2 and γ lamellae. Particles of TiB_2 , which were elongated in the extrusion direction (fig. 1), and a few carbon enriched precipitates were observed by scanning electron microscopy.

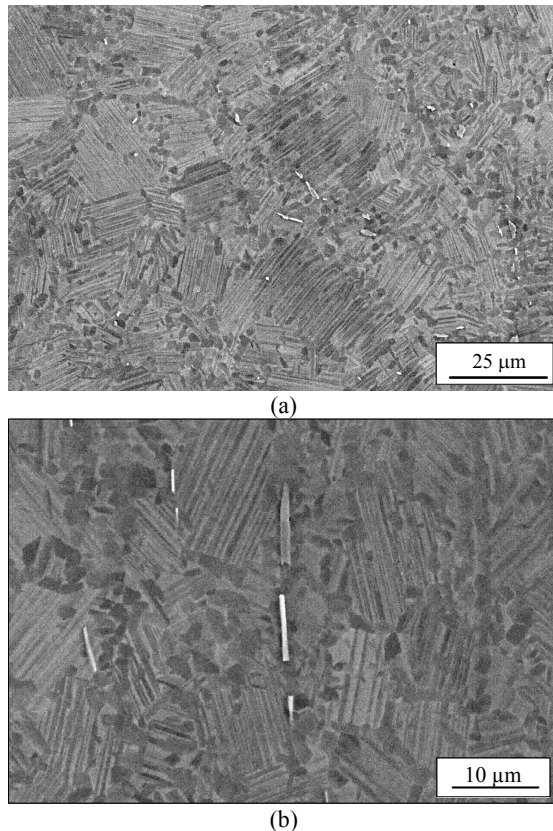


Figure 1: As-extruded microstructure of Gamma Met PX in the (a) transverse and (b) longitudinal directions.

Heat-treating at 1340°C for 40 min in vacuum produced a fully lamellar microstructure with equiaxed lamellar colonies averaging $325 \pm 45 \mu\text{m}$ in diameter, figure 2. As with the as-extruded microstructure, the lamellar microstructure contained TiB_2 precipitates, which were elongated in the extrusion direction. A reduction in hardness accompanied the heat treatment process. Vickers hardness averaged 431 and 374 VHN in the as-extruded condition and after 1340°C for 40 min, respectively. The reduction in hardness could be due to the recrystallization of the coarse new lamellar grains and/or additional microstructural changes (e.g. changes in size and distribution of precipitates).

Tensile

The tensile properties of as-extruded and lamellar heat treated Gamma Met PX (GMPX) are shown in figure 3. As-extruded GMPX has a high room temperature yield strength ($\sigma_{0.2\%y}$) and ultimate tensile strength (σ_{UTS}), averaging 1040 and 1130 MPa, respectively, which is in the same range as forged superalloys. The strength of as-extruded GMPX decreases with increasing deformation temperature; however, the σ_y and σ_{UTS} still averaged a relatively high 640 and 815 MPa at 760°C . The room temperature tensile ductility of GMPX, in the as-extruded condition, was also fairly high for a TiAl alloy, averaging 2.1% total (ϵ_T) and 1.3% plastic elongation (ϵ_p). The elongation of as-extruded GMPX remained fairly constant up to 650°C and then increased substantially, indicating a brittle-to-ductile transition temperature of around 700°C . Below the ductile-brittle

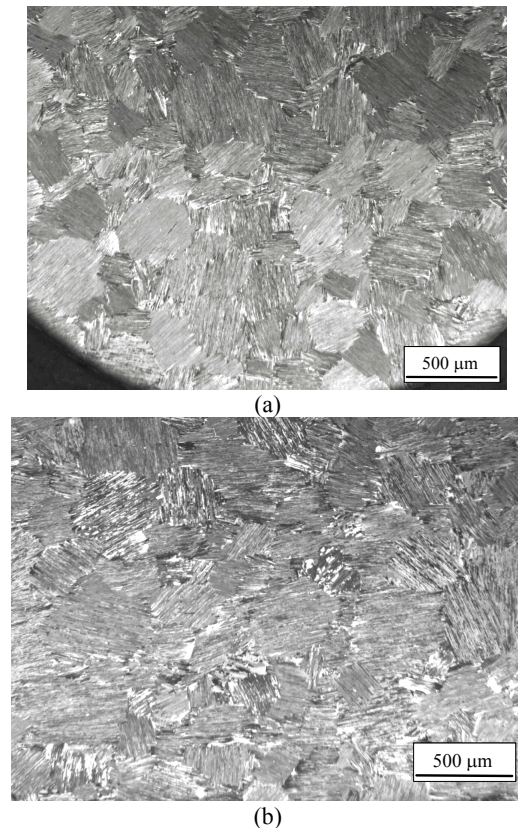


Figure 2: Microstructure of Gamma Met PX in the (a) transverse and (b) longitudinal direction after a lamellar heat treatment of 1340°C for 40 min in vacuum.

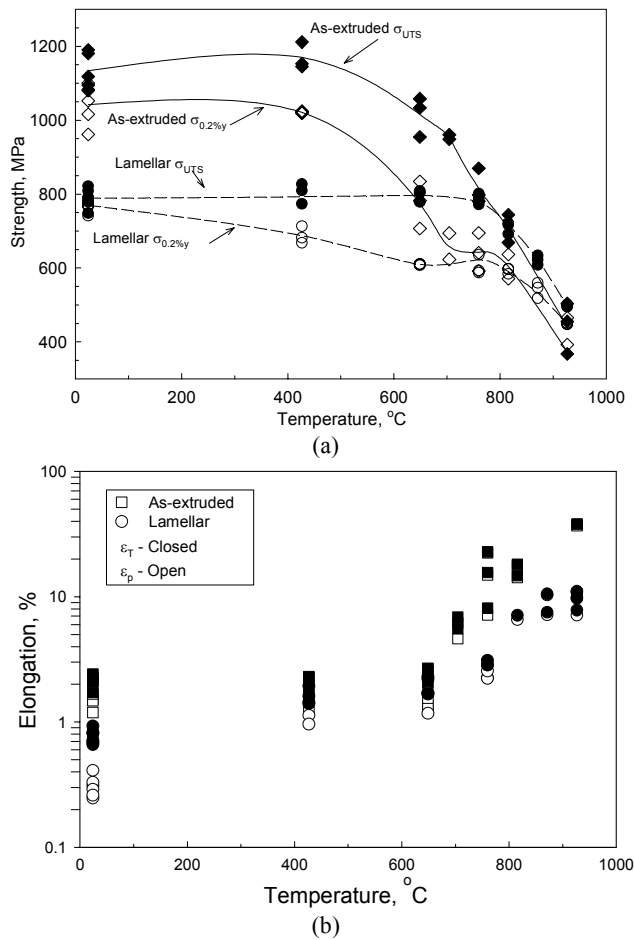
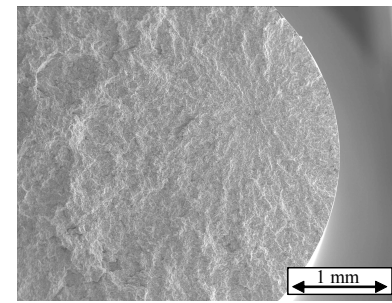


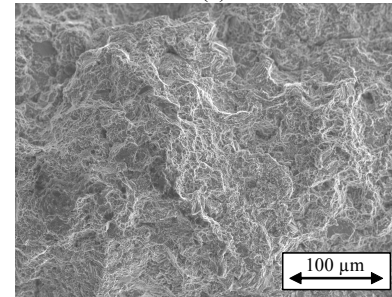
Figure 3: (a) Tensile strength and (b) ductility of Gamma Met PX in both the as-extruded and lamellar conditions as a function of temperature.

temperature, fracture took place in a macroscopically brittle manner with the majority of fractures originating at the surface. The flat nature of the room temperature, as-extruded fracture surfaces is illustrated in figure 4(a). Above the transition temperature, fracture became progressively more ductile, figure 4(b), with fracture origins again located primarily at the specimen surface. Recrystallization was observed on tensile fracture surfaces of specimens tested above 760 and at 926 °C, a classical ductile “cup and cone” fracture was observed.

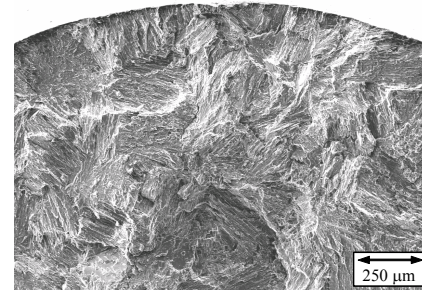
From room temperature to 760 °C, the lamellar heat treated GMPX had a lower strength than the as-extruded microstructure, with room temperature yield and ultimate tensile strengths averaging 770 and 790 MPa respectively (fig. 3(a)). At 760 °C and above, the strengths of the as-extruded and lamellar microstructures were equivalent. The room temperature elongation of the lamellar microstructure (fig. 3(b)) was significantly lower than the as-extruded material averaging only 0.77% total elongation, of which 0.31% was plastic. The total elongation of the lamellar GMPX increased to 1.65% at 425 °C and was equivalent to the as-extruded material at 650 °C. At 760 °C and above, the fully lamellar microstructure again exhibited lower ductility than the as-extruded microstructure.



(a)



(b)



(c)

Figure 4: Fracture surfaces of as-extruded Gamma Met PX show (a) a brittle fracture at 23 °C and (b) a ductile fracture at 815 °C. Fracture surface of lamellar heat treated GMPX at 23 °C (c) showing lamellar nature of fracture that was observed at all test temperatures.

Lamellar heat treated GMPX failed in interlamellar nature with a rough fracture surface at all test temperatures and fracture initiation sites were not discernable, figure 4(c).

A significant decrease in strain to failure was observed for samples which were machined first and then heat treated at 1340 °C for 40 min in vacuum to produce a fully lamellar microstructure. The decrease in elongation occurred in samples tested from room temperature to 760 °C. On the fracture surface of the samples, a 200 μm thick ring of fine grains was observed on the outer surface and electron dispersive spectroscopy on the fracture surface indicates that these grains have a lower Al content. Further investigation is required to confirm the Al loss during heat treatment and to determine the mechanism leading to the changed morphology and loss of ductility. The loss of Al from the surface may have led to the formation of Ti_3Al grains on the surface which may be responsible for the decreased strain to failure in machined and then heat treated samples. However, these fine grains may also have resulted from static recrystallization of the “cold worked” surface near regions deformed during

machining. Figure 3 includes only what is considered unaffected data, from samples which were machined from heat treated bars. The observed decrease in strain to failure is noted in this section as it probably influenced the fatigue properties of the lamellar microstructure specimens which were heat treated after machining.

As-extruded and lamellar GMPX tensile samples were exposed to 800 °C for 200 hr in air to determine the effect of high temperature exposure on tensile properties, figure 5. At room temperature, the samples failed in the grips for the threaded tensile samples with no plastic deformation. The specimen design was modified to a button-head design but the samples still failed in a brittle manner at the radius. The room temperature, as-extruded strengths and total elongation values plotted are not valid as the samples did not fail in the gage, but are the only available data. At 650 °C, the effect of the high temperature exposure was diminished but the total elongations still decreased from 2.4 to 1.9% due to the exposure. The room temperature ductility of specimens with lamellar microstructure was also decreased by the exposure but to a lesser degree, as two of the samples failed in the gage after undergoing some plastic elongation. The reason(s) for the loss of ductility following thermal exposure in air is under investigation and will be reported in the future.

Fatigue

High cycle fatigue specimens, with both as-extruded and lamellar microstructures, were step fatigue tested at 650 °C with a load ratio of 0.05, as were as-extruded GMPX specimens exposed to 800 °C for 200 hr. A bar chart in figure 6(a) compares the fatigue strength of GMPX in all three conditions to a baseline TiAl alloy, Ti-48Al-2Cr, 2Nb and also a Ni-base superalloy, IN718 [4]. The as-extruded fatigue strength averaged 760 MPa, close to the as-extruded yield strength at this temperature and nearly twice as high as the fatigue strength of Ti-48Al-2Cr-2Nb. The 650 °C fatigue strength of as-extruded GMPX did not diminish as a result of the high temperature exposure. Apparently, a total elongation of 1.9% at 650 °C, measured on exposed tensile specimens, is sufficient to maintain the fatigue properties. Fatigue fracture initiation sites were easily discernable for the as-extruded condition. Initiation occurred internally for both of the as-extruded fatigue specimens and at the surface for two of the three as-extruded and exposed samples, figures 6(b) and 6(c).

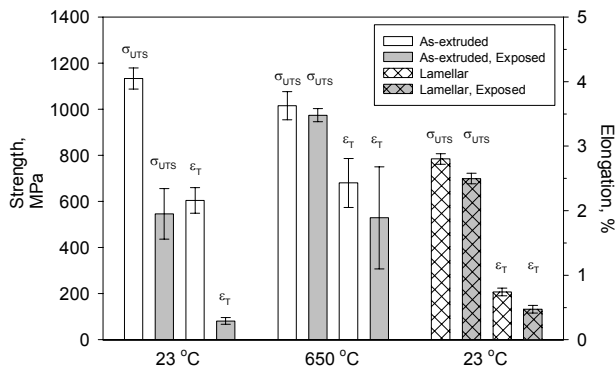


Figure 5: Effect of 800 °C/200 h/air exposure on tensile properties of the as-extruded microstructure at 23 and 650 °C and the lamellar microstructure at room temperature. Error bars represent 95% confidence intervals.

The fatigue strength of the lamellar material was significantly lower, averaging 470 MPa, compared to the as-extruded strength of 760 MPa. The lamellar heat treated fatigue samples had a translamellar fracture mode with multiple surface initiation sites around the circumference of the samples, figure 6(d). As discussed in another paper [5], the lamellar microstructure is conducive to easy crack initiation and lower fatigue strengths. The lamellar heat treatment led to lamellar colonies at least an order of magnitude larger than in the as-extruded samples. The larger colonies are believed to be the reason for the lower fatigue strengths. It has been shown that large lamellar colonies are easy initiation sites for fatigue cracks leading to reduced cyclic strengths and increased scatter [5]. The as-extruded material has poorly defined lamellar colonies as well as small gamma grains between the lamellae. These gamma grains may be beneficial to crack growth resistance. However, the lower strain to failure due to heat treatment after machining may also be a factor in the lower fatigue strength of the lamellar heat treated samples. Additional fatigue tests will be conducted on samples machined from heat treated bars.

Creep

As-extruded and lamellar heat-treated Gamma Met PX samples were tested in both compression and tension to determine the plastic flow behavior at strain rates ranging from 10^{-3} to 10^{-9} s⁻¹ between 727 and 1027 °C. Summary plots of the true compressive strain rate ($\dot{\epsilon}$) as a function of true flow stress (σ) and temperature (T) are given in figure 7, and the behavior of the as-extruded alloy is compared to that of the heat treated version in figure 8. The compressive creep behavior is well behaved and reproducible for both the as-extruded, figure 7(a), and lamellar microstructures, figure 7(b), and good agreement exists between the tensile and compressive properties. The as-extruded GMPX, figure 7(a), reaches superalloy-like creep strengths at faster strain rates and lower temperatures; however deformation of this form at low stresses and/or higher temperatures shows significant weakening, for example, 20 MPa yields $\sim 10^{-7}$ s⁻¹ at 927 °C. While strong, the lamellar GMPX (fig. 7(b)) appears to saturate at about 850 MPa under fast deformation conditions for temperatures ≤ 827 °C, at strain rates greater than 10^{-5} s⁻¹; on the other hand, this material maintains its strength in the higher temperature/slower strain rate regime: for example, a stress of about 100 MPa is required to deform at $\sim 10^{-7}$ s⁻¹ at 927 °C.

As-extruded and lamellar, heat-treated Gamma Met PX have nearly equivalent strengths at temperatures ≤ 827 °C and fast strain rates (figs. 8(a) and 8(b)) However, at higher temperatures and slower strain rates, the lamellar heat-treated material is significantly stronger than the as-extruded alloy, as can be visualized in figure 8(b) where the creep strengths in the 10^{-8} to 10^{-7} s⁻¹ strain rate range for as extruded Gamma Met PX at 827 °C is about the same as those displayed by heat treated Gamma Met Px at 1027 °C.

In the low stress region, the compressive flow stress-strain rate properties (fig. 7) can be described by a temperature compensated power law relationship (Eq. 1):

$$\dot{\epsilon} = A \sigma^n \exp(-Q/(RT)) \quad (1)$$

where A is a constant, n is the stress exponent, Q is the activation energy for deformation and R is the universal gas constant. At

high stresses, the power law breaks down and the data were not used to fit the equations. The as-extruded data fits the power law equation with an n of 2.3 ± 0.1 and an activation energy of 371 ± 16 kJ/mol. The lamellar microstructure was stronger, having a stress exponent of 4.8 ± 0.3 , and it also had a higher activation energy, 457 ± 24 kJ/mol. The difference in creep rate between the as-extruded and lamellar heat treated microstructure is most likely due to the larger grain size of the lamellar heat treated material [6] and the presence of the fine gamma grains at the lamellar borders in the as-extruded microstructure [6]. However, the fine details of the carbide, dislocation interactions may also be important.

The mechanical properties of GMPX are dependent on the microstructure (figs. 3 and 5 to 8). The tensile strength of the as-extruded microstructure was exceptionally high for a γ -TiAl alloy at all test temperatures [5]. The as-extruded microstructure achieved room temperature total elongations slightly higher than 2%, traditionally considered the lower limit for component design. The tensile strength of the as-extruded material is on the order of forged superalloys. On a density corrected basis, however, the specific strength would be double that of superalloys. While still stronger than traditional γ -TiAl alloys [5], the lamellar heat treated material had lower strengths than the as-extruded material from room temperature to 760 °C. Additionally, the lamellar

microstructure had significantly lower room temperature ductility than the as-extruded microstructure, figure 3(b). Fully lamellar TiAl typically has a lower ductility than TiAl with a duplex microstructure [7]. The strain to failure of GMPX increased significantly above 650 °C, indicating a brittle-to-ductile transition temperature of around 700 °C. Similar to the tensile strength, the fatigue strength of as-extruded GMPX was equivalent to a Ni-base superalloy (fig. 6(a)), even without correcting for density. The lamellar microstructure resulted in significantly lower fatigue strength (fig. 6(a)), likely a result of the grain growth that occurred during heat treatment. The lamellar microstructure had superior creep properties (fig. 8), particularly at high temperatures and slow strain rates, as compared to the as-extruded microstructure.

A high temperature exposure of 800 °C for 200 h in air embrittled both the as-extruded and lamellar tensile specimens as a significant decrease in elongation occurred during room temperature tensile tests of exposed samples (fig. 5). However, the high temperature exposure did not affect the 650 °C fatigue strength. Additional studies are planned to gain an understanding of this phenomena. It should also be noted that care must be taken in the heat treatment of Gamma Met PX. A lamellar heat treatment must be performed prior to machining of a specimen or component to avoid a loss of ductility.

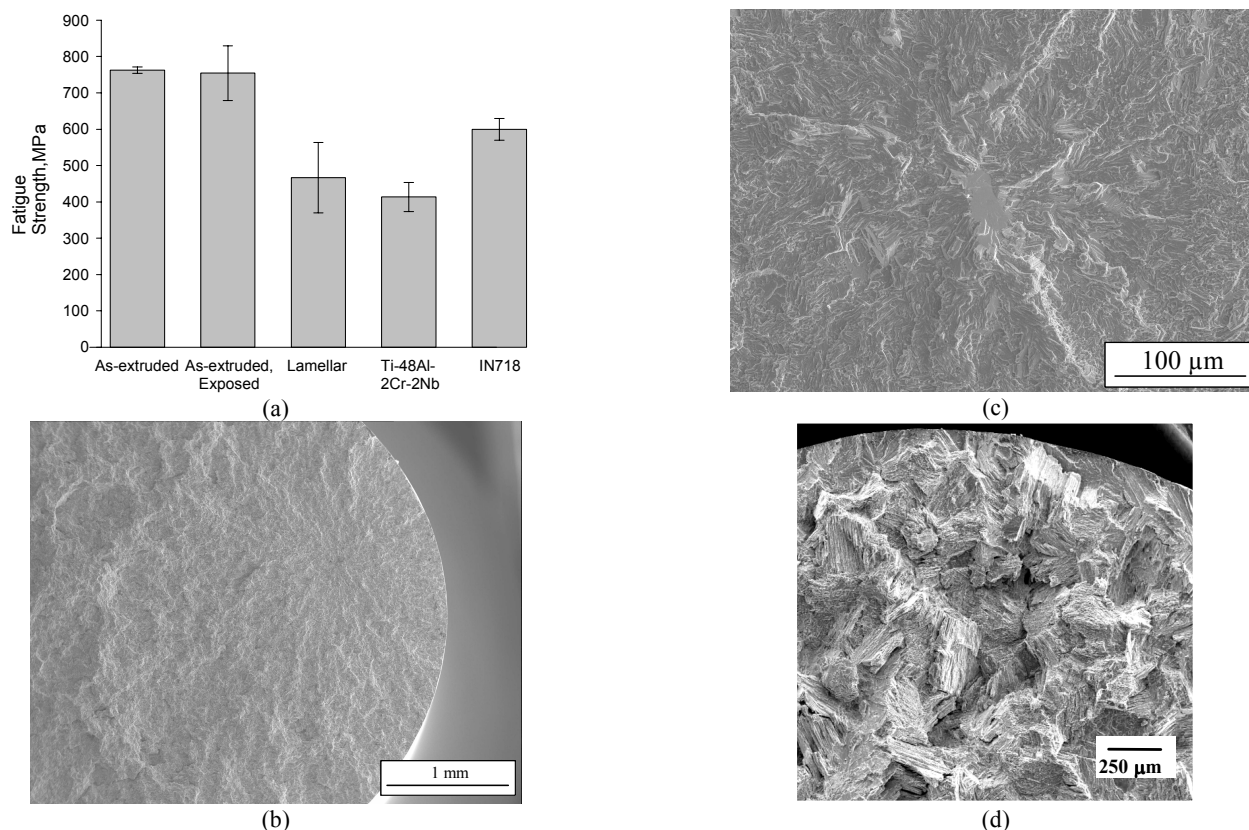
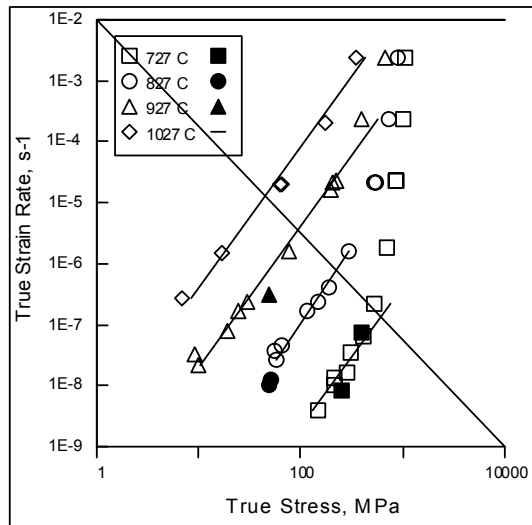
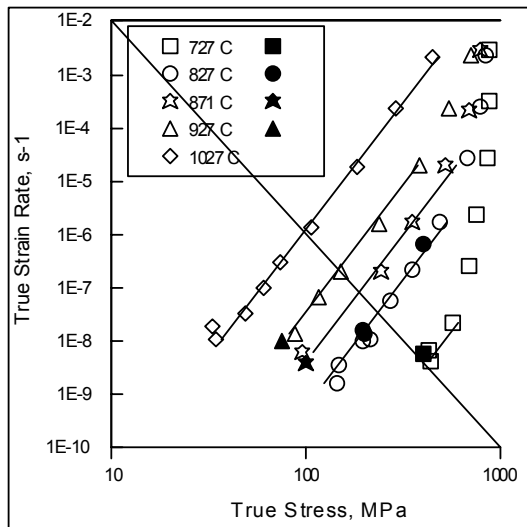


Figure 6: (a) 650 °C fatigue strength of Gamma Met PX in the as-extruded, as-extruded and exposed, and lamellar condition compared to traditional alloys. As-extruded fatigue fracture surfaces typically were relatively flat (b) and had easily identifiable initiation sites such as (c) at an internal lamellar colony in an as-extruded, exposed sample. (d) Lamellar fatigue samples typically initiated at multiple surface sites.



(a)

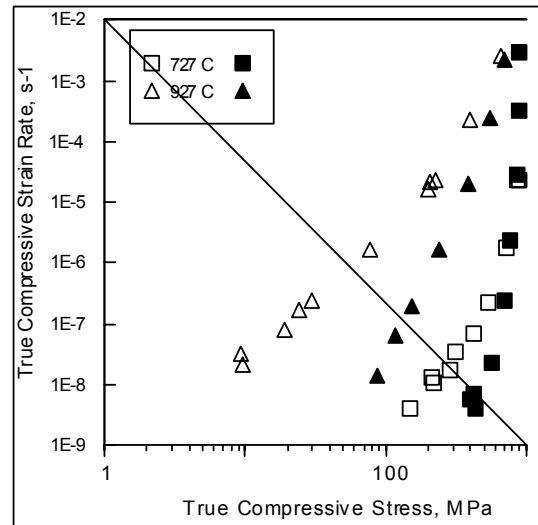


(b)

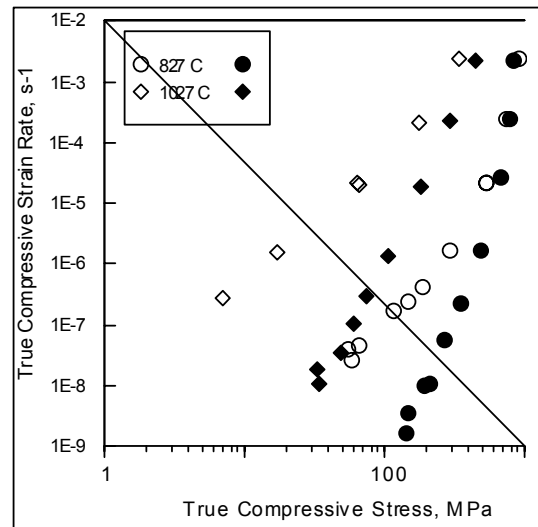
Figure 7: True strain rate—flow stress—temperature properties of Gamma Met PX tested in compression (open symbols) and tension (filled symbols). (a) as-extruded material and (b) heat treated alloy. The lines shown in each part are the result of temperature compensated power law fits of the compression data.

Summary and Conclusions

Gamma Met PX is a promising alloy as it possesses superior mechanical properties for a γ -TiAl alloy in both the as-extruded and lamellar condition. The mechanical properties depend on the microstructure with the as-extruded microstructure giving enhanced strength in both tensile and fatigue and the lamellar microstructure offering the best creep properties. The microstructure utilized will depend on the requirements of a particular application. A concern remains on the effect of air exposure on the room temperature ductility. Future efforts will be concentrated in this area.



(a)



(b)

Figure 8: True compressive strain rate—flow stress—temperature properties of as-extruded (open symbols) and heat treated (filled symbols) Gamma Met PX at (a) 727 and 927 °C and (b) at 827 and 1027 °C.

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